AN OPTICAL FIBRE REFLECTOMETER TO MONITOR REFRACTIVE INDEX CHANGES IN FLUIDS

J. Legendre and D. Crabtree

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ABSTRACT

A simple fibre-optic refractive index sensor for fluids is described. The sensing technique is discussed theoretically and some results are presented showing the linearity of the response. One all-fibre embodiment is described. The advantages of the sensing technique in a variety of situations are briefly mentioned. The particular advantages of the probe in clinical and biological applications are discussed more thoroughly.

RESUME

Un capteur simple de l'indice de réfraction de fluides utilisant d'une fibre optique est décrit. La théorie de la technique de détection est présentée et des résultats illustrent la linéarité de la réponse. Un appareil construit entièrement en fibres est aussi décrit. Les avantages de la technique pour diverses situations sont rapidement énumérées. Enfin, les avantages particuliers des utilisations biologiques et cliniques de la sonde sont donnés dans le détail.

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I. INTRODUCTION

The device described here is an optical reflectometer made of optical fibres. It is intended to measure a change in the refractive index of a fluid at a given point. Basically, the light reflected from an interface separating media of different refractive indices (such as the reflections seen from windows) is used to provide the signal which will indicate if one of the two media has changed its properties.

The device was originally conceived as a means of monitoring the presence or absence of signals in nerve fibres in biological specimens. In this application it is intended to replace the electrodes of various types currently in use. A more detailed discussion of the merits of the device in this context is to be found in Section IV.

It is felt that the potential applications of this measurement technique are quite widespread for several reasons. Firstly, any physical or chemical parameter (pressure, temperature, relative humidity, chemical concentration, etc.) which affects the refractive index of a fluid can be monitored by this technique. This would include pressure fluctuations due to acoustic energy in a gas or liquid or more simply the presence or absence of a liquid (liquid level sensor). Secondly, the sensor, which is the tip of an optical fibre (and is described in Section II), is simple, lightweight, relatively rugged, chemically inert, contains no moving parts or potentially hazardous electrical energy. Thirdly, the sensing fibre has a very small overall diameter. Typically such fibres have outer diameters of 0.125 mm. Even in applications which require the fibre to have a protective jacket, the overall diameter would remain quite small. This and the flexibility of these fibres mean that relatively awkward sites can be accessed with a minimum of difficulty. The small probe size also means that the location at which the measurement is made is known precisely (high spatial resolution). It is necessary, in this measurement technique, that the probe tip be immersed in a fluid. While it is assumed that in most applications changes in the fluid itself are of direct

interest, it is possible to envisage cases where the parameter of a solid (e.g., temperature) is first transferred to a liquid and then measured optically. Finally, the power requirements are very small. The transmitter and receivers of the optical signal would each require approximately 6 W. Any modulators and demodulators utilized would require about the same amount of power.

In the following sections, the sensing technique will be described in some detail, followed by a description of the reflectometer optics. Finally, a discussion of the potential merits of this technique when used to monitor biological specimens is presented.

II. DESCRIPTION OF THE SENSING TECHNIQUE

The signal in this device is derived by monitoring the changing reflected light irradiance as the refractive index of the medium at the end of a transparent fibre is varied. The probe is an optical fibre, typically of a low-loss type suitable for optical communications. A ray diagram illustrating propagation of one of the many possible rays (or waveguide modes) in a cylindrical fibre is shown in Fig. 1. The illustration assumes

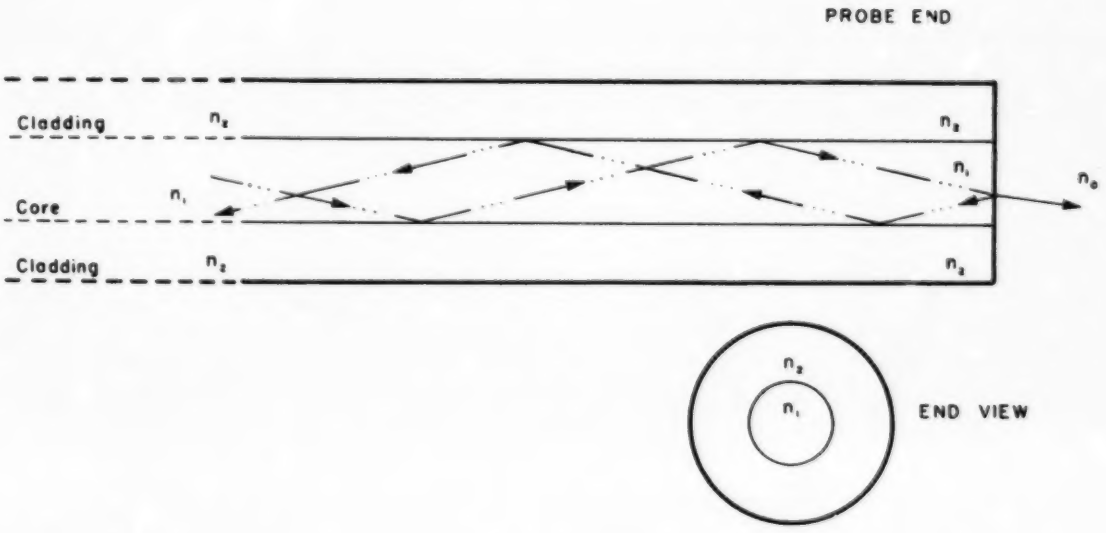

Figure 1 Light propagation in an optical fibre waveguide

a step-index fibre with a core refractive index n_1 and a cladding refractive index n_2. The use of step-index fibres is not essential in this sensor. Inhomogeneous waveguides of various refractive index profiles could be utilized. Referring to Fig. 1, the ray propagates down the fibre by multiple total internal reflections at the core-cladding interface. At the end of the fibre, the ray is partially transmitted and partially reflected at the discontinuity between the refractive index n_1 of the core and that of the surrounding medium n_0. The manner in which the transmitted portion of the light may be used will be mentioned later. At the moment, it is the reflected portion of the light which is of interest. It carries information concerning the optical properties of the surrounding medium at the end of the fibre. The reflection of a particular ray at the probe end of the fibre is governed by the Fresnel equations for dielectric media:

$$[1] \qquad r_{\perp} = \frac{n_1 \cos\theta_1 - n_0 \cos\theta_0}{n_1 \cos\theta_1 + n_0 \cos\theta_0}$$

$$[2] \qquad r_{\parallel} = \frac{n_0 \cos\theta_1 - n_1 \cos\theta_0}{n_0 \cos\theta_1 + n_1 \cos\theta_0}$$

where the angles and refractive indices are defined in Fig. 2, the sign convention is that used in reference 1, $r_{\perp}$ and $r_{\parallel}$ are amplitude reflection coefficients, and the subscripts "$\perp$" and "$\parallel$" refer to the two polarization states possible:

"$\perp$" - the electric field component of the incident beam is perpendicular to the plane of incidence

"$\parallel$" - the electric field component of the incident beam is parallel to the plane of incidence.

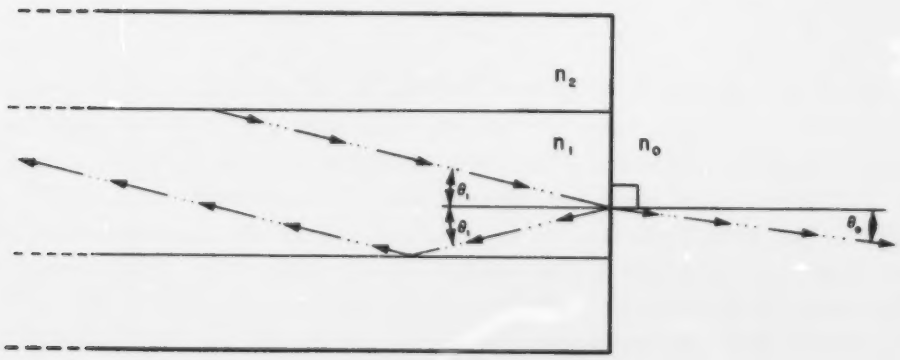

Figure 2 Reflection of a ray at the probe tip

In the case of a multimode optical fibre serving as the probe medium, the net reflection at the fibre end would be the summation of the reflections of each mode (with its characteristic value of θ_1), taking into account the relative amplitudes of the modes, their phases and their states of polarization. The situation would be simpler if a monomode fibre were used as a probe. In any case, whatever the net reflection coefficient, it must depend on the refractive index n_0 of the surrounding medium at the very tip of the cylindrical fibre. Any change in this refractive index would result in a change in the light reflected back down the fibre.

It is apparent that, in most cases of practical interest, important simplifications can be made to the involved relationship described above. Referring to equations [1] and [2], it is readily seen that, for normal incidence, $\theta_1 = 0$

$$[3] \qquad [r_{\parallel}] = [-r_{\perp}] = \frac{n_0 - n_1}{n_0 + n_1}$$

$$[4] \qquad R = r^2 = \frac{(\Delta n)^2}{(n_0 + n_1)^2}$$

where R is the reflectance, the ratio of the reflected to the incident flux (or power),

$$\Delta n = n_0 - n_1$$

For $\Delta n << 1$, equation [4] may be written

$$[5] \qquad R = \frac{(\Delta n)^2}{4n_1^2}$$

A trial was made in which the reflected signal strength was measured using a set of liquids of known indices. It can be seen in Fig. 3 that the relationship between signal strength and $(\Delta n)^2$ was quite linear. The reason for this circumstance may be seen in the fact that equations [1] and [2] do not result in strong variations of the amplitude reflection coefficients until relatively large values of θ_1 are achieved (see ref. 1, pages 75 - 76). The propagation mechanism down the fibre prevents such large values of θ_1 at the fibre end interface from being realized. The

assumption of normal incidence at the fibre tip is both justified and quite useful.

The method outlined may be implemented by using different fibre types (multimode, monomode; step index, graded index; glass, plastic). Essentially, the Fresnel reflection mechanism at the end of the fibre is utilized. The probe tip should be flat and normal to the axis of the probe fibre.

Earlier it was mentioned that a portion of the light incident on the fibre tip would be transmitted into the surrounding medium. This energy might be used to characterize that medium either through a fluorescence or scattering (e.g., Raman) mechanism. Re-radiated or scattered light could be collected by fibre and appropriately analysed. Although this technique could be quite powerful in some circumstances it is not the mechanism discussed in this paper.

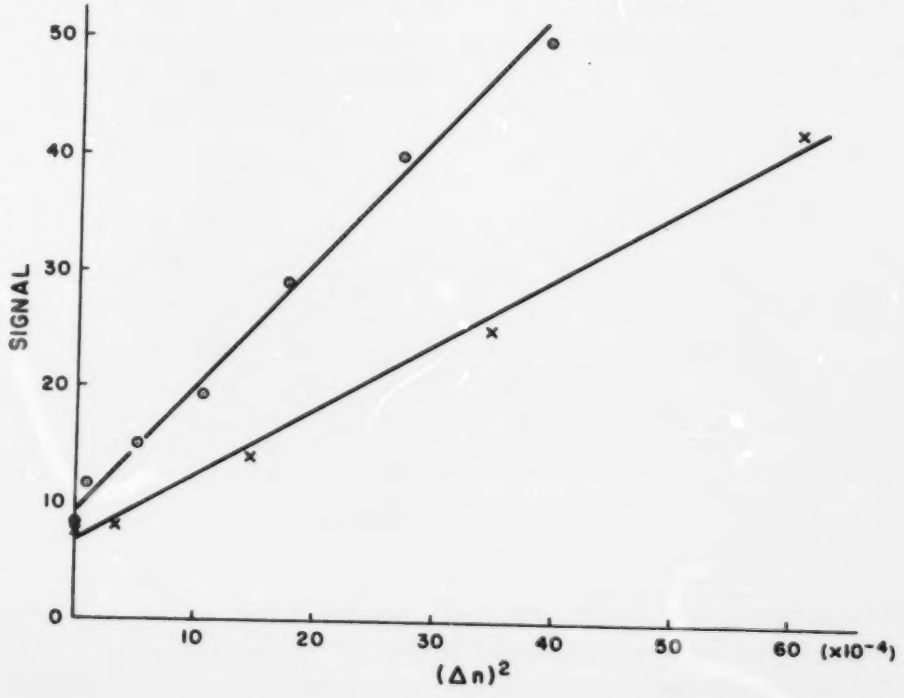

Figure 3 Measured reflected signal strength as a function of the square of the difference in refractive index between the fibre core and the medium at the fibre termination

III. DESCRIPTION OF THE REFLECTOMETER

A modified optical reflectometer (Fig. 4) is used for the measuring system. An optical signal from source S (which may be a laser) is launched into an optical fibre. The signal is first passed through a mode scrambler to ensure that all propagating modes of the fibre are excited. A portion of this signal is then coupled into another optical fibre by the directional coupler DC1. This light sample is detected at the detector D1 whose output is used to monitor any fluctuations in the light output of source S. The remainder of the light continues down the initial fibre to its end. At this interface the light undergoes a partial reflection due to the difference between the refractive index of the fibre core and that of the surrounding medium. The reflected light returns down the fibre where it is partially coupled into a third fibre by the directional coupler DC2. A detector, D2, at the end of this third fibre measures the arriving signal and in particular indicates any changes in this signal caused by refractive index fluctuations about the probe tip. Changes in signal level at D2 which are due to source fluctuations can be removed by using the output of D1 appropriately. Cladding mode strippers have been placed before and after coupler DC2 to remove any optical energy propagating in the cladding of the fibre.

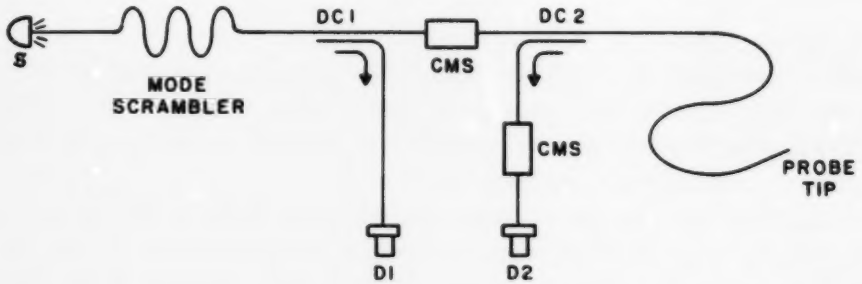

Figure 4 Fibre reflectometer configuration; S is an infrared light source bonded to the input fibre; DC1 and DC2 are three port directional couplers; CMS are cladding mode strippers; D1 and D2 are light detectors

IV. CLINICAL AND BIOLOGICAL APPLICATIONS OF THE FIBRE OPTIC REFLECTOMETER

A laboratory prototype of a fibre optic reflectometer has been developed at the National Research Council of Canada. In its present form it is possible to demonstrate the principle of operation by careful testing in a well controlled laboratory environment that is free of extraneous acoustic noise. However, the existing system is quite unsuitable for demonstrating viability of a desired measurement technique in a number of perceived applications.

The technique uses certain properties of the interface between the end of a light fibre and a surrounding conductive ionic medium. A relationship exists between the reflection coefficient at the interface and the concentration of the various ion species present. The measurement technique may therefore indicate when changes in sodium and potassium ion concentrations occur in excitable cells.

Currently, the perceived applications are

(1) a novel probe for detecting the activity of isolated groups of single units in the spinal cord: this will be an adjunct to a set of specialized microsurgical tools for neurosurgery of the spinal cord

(2) a new physiological research tool for excitable cells.

It is impossible to detect safely the activity of isolated groups of neurons in the spinal cord using electrophysiological techniques. Glass pipette electrodes can be fabricated to appropriate dimensions, but are too fragile to introduce inside the spinal cord as they would inevitably break, leaving debris in the constituent complex anatomical structures. Larger metallic electrodes made of platinum or silver are sufficiently rugged but would cause serious damage on penetration. The closest these electrodes can be safely placed to the cord or nerve roots is on the surface of the dura, the outermost membrane or 'meninge' surrounding the cord and other parts of the central nervous system (CNS). Electronic measurements conducted in this fashion suffer from the disadvantage that a minimum of two electrodes is required and their separation defines the spatial precision of the technique. Also the existence of conducting paths leading into the CNS of a patient is hazardous, especially in an operating room where electro-surgical equipment will most probably be in use. The risk of burning through accidental grounding or RF induction is unacceptable.

Furthermore, at the dura, signals are very weak, may only be 'recovered' from the thermal noise by averaging over many traces and are all but impossible to interpret owing to the spatial superposition of signals from all active units in the cord.

By contrast, the proposed technique would possess three advantages. Firstly, optic fibres have small dimensions appropriate to measurement technique envisaged. The site of the measurement is defined by the area of the interface with the test medium; this will afford the desired spatial precision. Secondly, the fibres are rugged and may even be bent with a very small radius of curvature without breaking. This would permit them to be inserted without risk either of compression damage to the spinal cord or of breaking and contaminating the cord with debris. Positioning the probe inside the spinal cord instead of at the surface of the dura would enhance the signal-to-noise ratio making averaging unnecessary and real-time operation possible. This would also solve the problem of spatial superposition of signals. A third advantage is that optic fibres are insulators and would introduce no additionally hazardous conductive paths inside the CNS during surgery.

Electrophysiology is a discipline dedicated to the study of excitable cells and tissues. As its name implies, it is an empirical science relying on the detection of electrical potentials to gain insights into the underlying physiological processes. These potentials are in fact electrochemical in nature and result indirectly from local changes in ionic concentrations in excitable cells. One may ask 'why not detect these ionic concentration changes directly?' The answer is simple; although ion selective electrodes exist, they have time constants on the order of seconds whereas the bandwidth of the processes of interest to physiologists is several kilohertz. The proposed technique, if viable, should solve this problem. It would also permit a more direct experimental determination of ion concentrations than is available to physiologists now. Optimistically, the technique may possess some additional advantages that the experimentalist would value. Working with electrodes is a laborious pastime: they are subject to breakage and degradation and often must be replaced during the course of an experiment. The proposed technique may solve these problems since the probes are more rugged. Additionally the technique should pave the way to new insights in physiology by providing an analog of activity in excitable cells which is not now available to the experimentalist.

REFERENCES

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